

# Gamma-rays and cosmic-rays from a pulsar in Cygnus OB2

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## ABSTRACT

We argue that gamma-ray sources observed in the direction of the Cyg OB2 association in the GeV and TeV energy range are due to a pulsar which was created by a supernova a few tens of thousands years ago. The GeV emission is produced by a middle-aged pulsar, a factor of two older than the Vela pulsar. The TeV emission is produced by high energy hadrons and/or leptons accelerated in the pulsar wind nebula. We suggest, moreover, that the excess of cosmic rays at  $\sim 10^{18}$  eV, observed from the direction of the Cygnus region, can also be related to the appearance of this very energetic pulsar in the Cyg OB2 association. A part of relativistic hadrons, captured in strong magnetic fields of a high density region of the Cyg OB2, produce neutrons and  $\gamma$ -rays in collisions with the matter. These neutrons can arrive from the Cyg OB2 creating an excess of cosmic rays.

**Key words:** gamma-rays: individual: Cyg OB2 – ISM: clouds – cosmic rays – pulsars: general – gamma-rays: theory – radiation mechanisms: non-thermal

## 1 INTRODUCTION

The Cygnus OB2 is the largest massive galactic association at a relatively small distance of 1.7 kpc. It has the diameter of  $\sim 60$  pc and the core radius of  $\sim 14 \pm 2$  pc. The total  $H_2$  mass of the Cyg OB2 derived from the CO survey is  $\sim 3.3 \times 10^5 M_\odot$  (Butt et al. 2003), and the total stellar mass is  $(4 - 10) \times 10^4 M_\odot$  (Knödlseeder 2000). It contains many massive stars of the OB type ( $\sim 2600 \pm 400$ ) and O type ( $\sim 120 \pm 20$ ) (Knödlseeder 2000). The typical main sequence evolution lifetime of the massive O type stars is of the order of a few  $10^6$  yrs and B type stars a few tens of  $10^6$  yrs. Massive O type stars should pass through the Wolf-Rayet phase and explode as supernovae. It is expected that very fast pulsars are created in explosions of such massive stars at a rate of about one per a few  $10^4$  yrs within the Cyg OB2. This rate can be much higher if most of these massive stars are of similar age. The pulsars, created  $\sim 10^4$  yrs ago, should resemble the Vela type pulsars (e.g. Vela pulsar, PSR 1706-44), which are strong sources of pulsed  $\gamma$ -rays in the hundred MeV-GeV energies (EGRET observations, Kanbach et al. 1994, Thompson et al. 1996). These pulsars are also surrounded by relatively small pulsar wind nebulae (PWNe), which are sources of TeV  $\gamma$ -rays (Chadwick et al. 2000, Kifune et al. 1995, Chadwick et al. 1998).

The Cygnus region is difficult to observe in high energies due to its very complex structure and location on the galactic plane. The analysis of the EGRET data from different viewing periods revealed a few sources in a relatively small field of view containing the Cyg OB2: 2EG J2033+4112 (Mori et al. 1997), GeV J2035+4214 (Lamb

& Macomb 1997), GRO J2034+4203 (Reimer, Dingus & Nolan 1997), 3EG J2033+4118 (Hartman et al. 1999). The first source is interpreted by the authors as caused by the massive binary Cyg X-3. The other sources may be due to the same object in the Cyg OB2, according to Butt et al. (2003).

Recently, the HEGRA group has reported the discovery of an unidentified, steady, TeV source at the edge of the 95% error circle of the source 3EG J2033+4118 (Aharonian et al. 2002). The spectrum of this source is rather flat (differential spectral index  $-1.9 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$ ), with the flux about two orders below the flux observed from 3EG J2033+4118. Moreover, there is an indication that the TeV source is extended with a radius of  $5.6'$  (Aharonian et al. 2002), confirmed in the new analysis of the HEGRA data by Rowell & Horns (2002).

The discovery of TeV source has led to a more careful analysis of the X-ray observations of Cyg OB 2 from the ROSAT and Chandra telescopes (Mukherjee et al. 2003, Butt et al. 2003). None of the several X-ray sources detected by the Chandra in the region with  $\sim 11'$  diameter around the TeV source was particularly prominent (Butt et al. 2003). Mukherjee et al. (2003) notes only one interesting variable source which lies  $7'$  from the TeV centroid with the flux of  $2 \times 10^{-12}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ . It might be a quiescent low-mass X-ray binary containing a neutron star or a black hole. However, weak diffuse X-ray emission has also been observed, with the intensity of  $1.3 \times 10^{-12}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  in 0.5-2.5 keV and  $3.6 \times 10^{-12}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  in 2.5-10 keV (Butt et

al. 2003). This is more than ten times as bright as the sum of all the point-like sources.

Recent analysis of the arrival directions of cosmic rays with energies of  $\sim 10^{18}$  eV by the AGASA group shows the excess of particles from the direction of the Galactic Center (Hayashida et al. 1999a, confirmed by the SUGAR analysis, Bellido et al. 2001), and from the direction of the Cygnus region. The second excess has a significance of  $3.9\sigma$  (3401 events with the background of 3148) in the energy range  $10^{18} - 10^{18.4}$  eV (Hayashida et al. 1999b). We suggest that this excess of EHE particles can also be related to the high energy processes occurring in the massive Cyg OB2 association.

The possibility that  $\gamma$ -rays are produced by massive young stellar clusters, as a result of acceleration of particles in the winds or shocks produced by the early type stars, has been frequently discussed in the past (with the application to the Cyg OB2, see e.g. Chen, White & Bertsch 1992, Manchanda et al. 1996, Benaglia et al. 2001). Aharonian et al. (2002) discusses such general scenario, suggesting that the TeV emission may originate in collisions of hadrons with a dense cloud. These authors also propose that  $\gamma$ -ray emission may originate in the inverse Compton scattering by electrons, which are accelerated by a jet-driven termination shock expelled from a microquasar, e.g. Cyg X-3 (see Aharonian & Atoyan 1998). Butt et al. (2003) argue that the TeV emission is more likely to originate in collisions of hadrons with the matter than in the leptonic processes. Hadrons might be accelerated to PeV energies in collisions of strong stellar winds.

In this paper we interpret the variety of high energy processes connected with the Cyg OB2 association by applying the model in which the basic role is played by a young pulsar, born in this association about  $\sim 10^4$  yrs ago. It is shown that the observed GeV emission can be due to the Vela type pulsar present inside or close to the Cyg OB2 (Sect. 3). The TeV  $\gamma$ -ray emission originates in the pulsar wind nebula as a result of interactions of hadrons and leptons (Sect. 4). The observed excess of cosmic rays from the direction of the Cygnus region at energies of  $\sim 10^{18}$  eV is due to neutrons, which are dissolved from heavy nuclei in their interactions with the matter of the Cyg OB2 (Sect. 5). We show that if a small part of nuclei, which escaped from the PWN, is captured in a strong magnetic field of dense regions of the Cyg OB2 association, the flux of neutrons can explain the observed cosmic ray excess from the Cygnus region.

## 2 A MODEL FOR HIGH ENERGY PROCESSES IN THE CYG OB2

Let us assume that a very energetic pulsar is formed in a core collapse of one of the massive stars in the Cyg OB2 association. The massive O type stars should evolve through the Wolf-Raeyt phase during which the star loses a significant part of its envelope, rotates fast, and has strong surface magnetic fields. The Wolf Raeyt stars are probably progenitors of neutron stars with extreme parameters (period, surface magnetic field) which allow acceleration of particles to very high energies. Following the recent works (e.g. Gallant & Arons 1994, Blasi, Epstein & Olinto 2000) we assume that such neutron stars can accelerate heavy nuclei in their

wind zones (e.g. in the mechanism called magnetic sling-shot, Gunn & Ostriker 1969). Arons and collaborators (see e.g. Arons 1998) argue that the iron nuclei can reach energies equal to a significant part,  $\chi$ , of the total potential drop through the pulsar polar cap region,

$$E_{\text{Fe}} = \chi Ze\Phi_{\text{open}}, \quad (1)$$

where,  $Ze$  is the charge of the iron nuclei,  $\Phi_{\text{open}} = \sqrt{E_{\text{rot}}/c}$  is the maximum potential drop across the polar cup of the pulsar,  $E_{\text{rot}}$  is the rate of rotational energy lost by the pulsar,  $\chi \leq 1$ , and  $c$  is the velocity of light. These nuclei are accelerated with efficiency corresponding to the Goldreich & Julian current at the light cylinder radius (Goldreich & Julian 1969). Due to the rotational energy losses of the pulsar, the energies of nuclei injected into the expanding nebula drop with time. Based on the modelling of the Crab Nebula, Arons (1998) argues that  $\chi$  should be not very far from one. Assuming  $\chi = 0.5$ , we use the following prescription for the evolution of the Lorentz factor of injected Fe nuclei with time

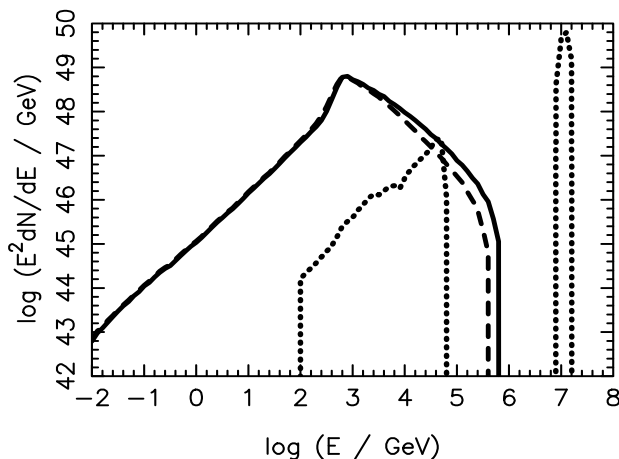
$$\gamma_{\text{Fe}} = E_{\text{Fe}}/m_{\text{Fe}} \approx 4 \times 10^9 B_{12} P_{\text{ms}}^{-2}, \quad (2)$$

where  $m_{\text{Fe}}$  is the mass of the iron nuclei,  $B = 10^{12} B_{12}$  G is the surface magnetic field of the pulsar, and  $P = 10^{-3} P_{\text{ms}}$  s is the pulsar period which evolves in time  $t$  (in seconds) due to the rotational energy losses according to

$$P_{\text{ms}}^2 = P_{0,\text{ms}}^2 + 2 \times 10^{-9} t B_{12}^2, \quad (3)$$

where  $P_{0,\text{ms}}$  is an initial period of the pulsar.

In order to obtain the equilibrium spectra of these nuclei inside the nebula at a specific time, we construct a simple time dependent model for the expanding nebula, basing on the early papers which discuss the evolution of a supernova envelope under the influence of a young pulsar (e.g. Ostriker & Gunn 1971). This model takes into account possible acceleration of the nebula due to the energy supply by the pulsar. This has influence on the main parameters of the nebula, i.e. an expansion velocity, a shock radius, an outer radius, and a magnetic field inside the nebula. The details of such a model are described in Sect. 2 of Bednarek & Bartosik (2003). The equilibrium spectra of nuclei are obtained by integrating their injection spectra at a specific time over the activity period of the pulsar, and taking into account different processes such as: (1) inelastic collisions of nuclei with the matter (important at an early phase); (2) the adiabatic energy losses of particles due to expansion of the nebula; and (3) the escape of nuclei from the nebula. We include all these processes as it has been already done in our previous papers (see sect. 4 in Bednarek & Protheroe 2002). However, in order not to complicate the model too much, the gravitational energy losses of the pulsar are neglected. We also include partial disintegration of iron nuclei, extracted from the neutron star surface, during their propagation through the radiation field of the pulsar outer gaps in the inner pulsar magnetosphere following Bednarek & Protheroe (1997). Even for the pulsars with the age  $2 \times 10^4$  years, the iron nuclei still lose on average one nucleon in collisions with the nonthermal radiation in the pulsar's outer gap. Nucleons (protons, neutrons) dissolved from the iron nuclei in this process are added to the spectrum of nuclei injected into the nebula. The example equilibrium spectrum of nuclei, which are still inside the nebula at  $2 \times 10^4$  years after supernova



**Figure 1.** The equilibrium spectra of leptons and different types of nuclei (dotted curve) inside the nebula at the time  $2 \times 10^4$  yrs after supernova explosion. The initial period of the pulsar is 2 ms and its surface magnetic field  $6 \times 10^{12}$  G, and the initial expansion velocity of the supernova remnant is  $2000 \text{ km s}^{-1}$ , and its mass is  $4 M_{\odot}$ . The spectra of leptons are shown for two radiation fields inside the nebula: (1) the synchrotron photons (SYN) and the microwave background radiation (MBR) (full curve), and (2) SYN, MBR, and the infrared photons with temperature 100 K and energy density 5 times higher than the MBR (dashed curve).

explosion, is shown in Fig. 1. A higher energy bump in the spectrum of hadrons contains heavy nuclei of the iron group. Their energies are limited to a relatively narrow range due to the adiabatic energy losses of nuclei injected at the earlier phase and the escape of more energetic nuclei from the nebula. A lower energy bump in the spectrum of hadrons contains protons from disintegrations of heavy nuclei during their propagation in the pulsar outer gap and from collisions of nuclei with a dense matter of the nebula at an early stage after supernova explosion. All the medium mass nuclei with relatively large Lorentz factors, produced in collisions of nuclei with the matter of the nebula at an early phase after the explosion, have already managed to escape from the nebula. The equilibrium spectra of nuclei inside the nebula at a specific time allow us to calculate the spectra of  $\gamma$ -rays from decay of pions, produced by nuclei in collisions with the matter of the nebula.

According to Hoshino et al. (1992), relativistic heavy nuclei can transfer a part of their energy,  $\xi$ , to relativistic positrons in the process of resonant scattering in the region above the pulsar wind shock. As a result, positrons are accelerated with the power law spectrum with the index  $\alpha \sim 2$  between  $m_e c^2 \gamma_{Fe}$  and  $\gamma_{Fe} m_{Fe} c^2 / Z$ , where  $m_e$  is the mass of the electron. The injection spectra of these positrons evolve in time due to the change of energies and injection rate of iron nuclei with the pulsar period. The equilibrium spectra of positrons inside the nebula at a specific time are calculated by taking into account their radiation energy losses on bremsstrahlung, synchrotron, and inverse Compton (IC) processes, and due to the adiabatic losses caused by an expansion of the nebula as it was shown in Sect. 4.2 in Bednarek & Bartosik (2003). The efficiencies of specific energy loss processes are determined by the evolving in time parameters of the nebula. The bremsstrahlung process depends on the average density of matter inside the

nebula which can be easily evaluated for the known total mass of the nebula and its radius at a specific time. The synchrotron losses of leptons are determined by the magnetic field strength inside the nebula which is estimated from the known dependence of the magnetic field inside the pulsar inner magnetosphere and the pulsar wind zone (see for details Eq. 7 in sect. 2 in Bednarek & Bartosik 2003). The evolution of the magnetic field strength in the pulsar wind postshock region is shown in Fig. 2b, for the example parameters of the pulsar and the nebula. The IC losses of leptons is more difficult to estimate. For relatively old nebulae the energy density of background radiation is dominated by the microwave background radiation (MBR), and possibly infrared background and optical background. Since the optical background created by the massive stars inside the Cyg OB2 becomes important only for low energy leptons,  $\leq 100 \text{ GeV}$ , we do not consider their influence on the equilibrium spectrum of leptons inside the nebula. The radiation field inside relatively young nebulae is dominated by the synchrotron photons produced by leptons inside the nebula which spectrum is determined by the conditions inside the nebula in the past. Therefore, in order to estimate the density of synchrotron photons at a specific time we apply simple model for the evolution of nebula and include the above defined prescription for the injection of particles and the evolution of the radiation processes. It is assumed that only a part of the whole nebula radiate efficiently. This might be motivated by the observed anisotropic injection of particles into the pulsar wind nebulae which manifests itself by the presence of X-ray torus in the equatorial plane of the pulsars (e.g. the X-ray torus around  $\sim 20^\circ$  of the equatorial plane observed in the Crab Nebula). We estimate the density of synchrotron photons inside the nebula assuming that leptons are injected and radiate only within the part of the nebula limited by the above mentioned  $20^\circ$  torus. The evolution of the synchrotron background inside the nebula at a specific time after supernova explosion is shown in Fig. 2c. It is clear that inside the nebulae older than  $\sim 3 \times 10^3$  yrs, the IC energy losses of leptons on synchrotron photons becomes negligible. Only scattering of the MBR and possibly the infrared radiation, produced by the hot gas inside the nebula, plays important role. Fig. 2a shows the equilibrium spectra of leptons inside the nebula at a specific time after supernova explosion. The lower energy part of the spectrum of leptons is formed by leptons which were injected relatively early after supernova explosion and lose energy at latter time mainly due to the adiabatic expansion of the nebula. Therefore, the low energy cut-off in the spectrum of leptons, present between 0.1 - 0.01 GeV (Fig. 2a), shifts to lower energies with the evolution of the nebula. The efficient synchrotron cooling determines the shape of the spectrum in the higher energy range when the nebula is young and the magnetic field is strong. This process is responsible for the power low spectrum with the index close to 2 (seen in Fig. 2a) at the time  $10^2$  yrs. On the other hand, the spectrum of leptons at higher energy part at the latter phase of expansion of the nebula is formed by freshly injected leptons which are not able to cool to low energies fast enough due to the weak magnetic and photon fields inside the nebula.

Described above pulsar-supernova model is applied to a variety of high energy processes observed from the direction of the Cyg OB2 association. To describe self-consistently all

the observed radiation processes, we postulate that the pulsar was born with the initial period  $P_0 = 2$  ms and the surface magnetic field  $B = 6 \times 10^{12}$  about  $t = 2 \times 10^4$  yrs ago, within or close to the dense core of the OB2 association. If this pulsar loses energy mainly on emission of electromagnetic radiation, then its present period should be  $\sim 210$  ms (see Eq. 3). A pulsar with such parameters resembles the Vela type pulsars, i.e. it should produce the pulsed  $\gamma$ -rays with luminosity comparable to the Vela pulsar itself or e.g. PSR 1706-44. Note that these pulsars are surrounded by the synchrotron pulsar wind nebulae from which the steady TeV  $\gamma$ -ray emission is observed. It is assumed that the supernova exploded close to the dense regions of the Cyg OB2 in the medium with the density of at least  $\sim 30 \text{ cm}^{-3}$  (Butt et al. 2003), and the initial velocity of the bulk mass of the supernova envelope is  $2000 \text{ km s}^{-1}$  and its mass is  $4 M_\odot$  (as derived for the Crab Nebula, Davidson & Fesen 1985). For these parameters of the pulsar and the supernova, the velocity of the supernova front wave after  $2 \times 10^4$  yrs is  $\sim 100 \text{ km s}^{-1}$ . Such a low velocity front wave can be difficult to observe due to its distortions in the interactions with the clumpy high density medium of the Cyg OB2 association. In fact, the supernova remnant shell-like structure has been revealed near the TeV source region in the CO, HI, and radio emission maps (Butt et al. 2003). The average density of matter inside this shell ( $\sim 30 \text{ cm}^{-3}$ ) is much smaller than the average density of matter in the core of the Cyg OB2 equal to  $\sim 300 \text{ cm}^{-3}$ , calculated from the total mass of the Cyg OB2  $\sim 10^5 M_\odot$  (Butt et al. 2003) and its core radius  $\sim 15 \text{ pc}$  (Knödlseeder 2000).

In the forthcoming sections we argue that the GeV and TeV  $\gamma$ -ray emission from the Cygnus region can be due to the Vela type pulsar and its nebula, and the excess of  $\sim 10^{18}$  eV cosmic rays is due to the neutrons from disintegration of very relativistic nuclei which were accelerated soon after the pulsar formation and are still present inside the high density region of the Cyg OB2 association.

### 3 3EG J2033+4118 - A VELA TYPE PULSAR

The spectrum of 3EG J2033+4118 was originally described as consistent with a simple power law with the index of  $1.96 \pm 0.10$ , but a double power law or a power law with the exponential cut-off give better fits (Bertsch et al. 2000, Reimer & Bertsch 2001). This source is classified as being a non-variable (see discussion in Butt et al. 2003), in contrary to its earlier classification as a variable by Mukherjee et al. (2003). 3EG J2033+4118 is believed to be located within the Cyg OB2 association (Aharonian et al. 2002, Mukherjee et al. 2003, Butt et al. 2003).

Interestingly, the  $\gamma$ -ray emission of this source resembles the spectra of the middle aged pulsars (the break at  $\sim 1 \text{ GeV}$  and the sharp cut-off at a few tens of GeV, required in the spectrum of 3EG J2033+4118 by the level of TeV emission observed by the HEGRA telescope). Therefore, we suggest that the  $\gamma$ -ray source 3EG J2033+4118 is caused by a yet undiscovered Vela type pulsar within the Cyg OB2 association. In fact, also the level of the  $\gamma$ -ray emission from 3EG J2033+4118 is very close to that observed from the Vela type pulsars. Fig. 3 shows the spectra of the Vela pulsar (V), after its re-normalization from the

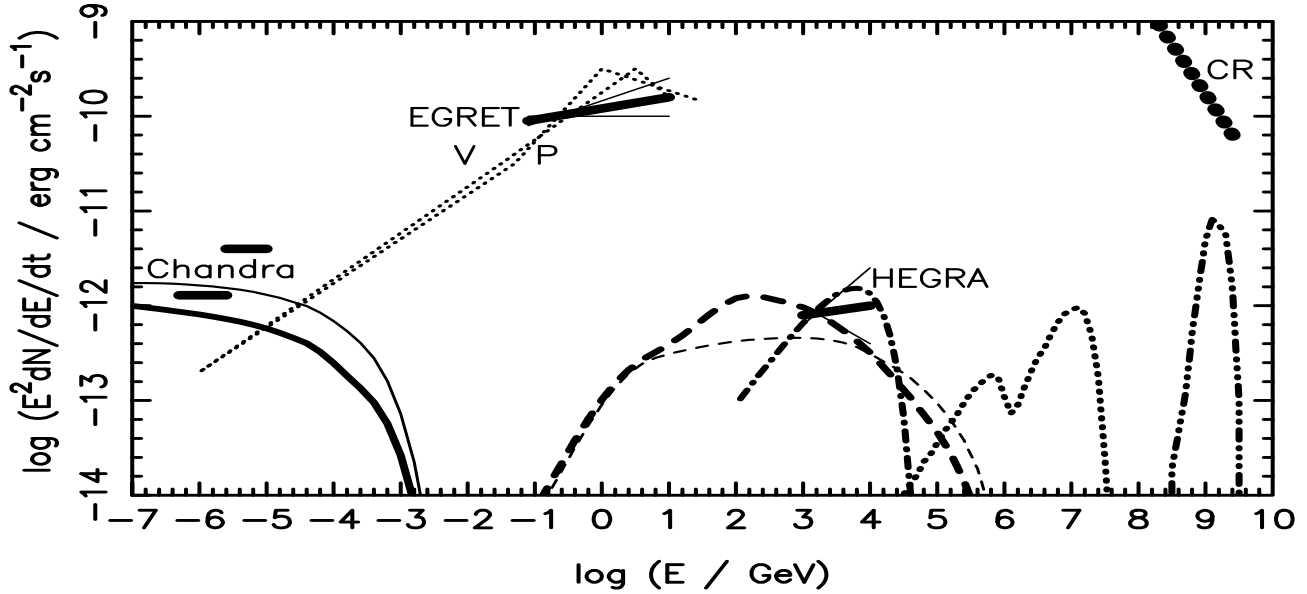
Vela pulsar distance  $\sim 500 \text{ pc}$  to the distance to the Cyg OB2  $\sim 1.7 \text{ kpc}$ , and the PSR 1706-44 (P), which is at a similar distance as the Cyg OB2. The spectrum of the Vela pulsar is measured by the EGRET (Thompson et al. 1997), COMPTEL (Schönfelder et al. 2000), OSSE (Strickman et al. 1996), and RXTE (Harding et al. 2002). The spectrum of PSR 1706-44 is measured by the EGRET (Thompson et al. 1996) and constrained by the upper limits on the pulsed emission in the X-rays by the ROSAT and ASCA (Becker et al. 1995, Finley et al. 1998). It is clear that the  $\gamma$ -ray spectra of these sources are very similar. The present parameters of the pulsar inside the Cyg OB2 can be like those ones in the example considered in the previous section, i.e. the age of  $2 \times 10^4$  yrs, the present pulsar period of  $\sim 210$  ms, and the surface magnetic field of  $6 \times 10^{12} \text{ G}$ . We encourage the searches of such order of periodicity in the  $\gamma$ -ray data of the source 3EG J2033+4118.

### 4 TEV J2032+4130 - A PULSAR WIND NEBULA

As it has already been mentioned, the Vela type pulsars are surrounded by the non-thermal nebulae observed in the X-rays and TeV  $\gamma$ -rays. The present parameters of the pulsar, which we propose as responsible for the high energy processes in the Cyg OB2, are the closest to the pulsar PSR 1706-44. It lies at a similar distance, equal to  $\sim 1.8 \text{ kpc}$ , has the present period of 102 ms, and the surface magnetic field of  $3.1 \times 10^{12} \text{ G}$ . The level of non-thermal X-ray emission from the nebula around PSR 1706-44, observed by the ROSAT and ASCA (Becker, Brazier & Trümper 1995, Finley et al. 1998), is close to the level of diffuse X-ray emission observed by the Chandra from the direction of the  $\gamma$ -ray source TeV J2032+4130 in the Cyg OB2 (Butt et al. 2003).

The X-ray to TeV  $\gamma$ -ray emission from the nebula around PSR 1706-44 has recently been interpreted in terms of the hadronic, leptonic model for the high energy radiation from the pulsar wind nebulae (Bednarek & Bartosik 2003). The relatively low level of X-ray emission from this nebula (as compared to e.g. the Crab Nebula) is explained if the efficiency of positron acceleration by the nuclei injected by the pulsar is relatively low  $\xi \approx 0.08$ . On the other hand, in order to explain the level of the TeV  $\gamma$ -ray emission, an additional target of infrared photons inside the nebula is required, apart from the low energy synchrotron photons and the MBR (see Fig. 8 in Bednarek & Bartosik 2003). The  $\gamma$ -rays, produced in collisions of hadrons with the matter of the nebula, do not contribute essentially to the TeV  $\gamma$ -ray spectrum observed from this nebula due to the relatively low density of matter around PSR 1706-44.

In contrast to the PSR 1706-44 and its nebula, which were modeled by the pulsar with the initial period of 15 ms, here we postulate that the pulsar in the Cyg OB2 was born in a recent supernova explosion of one of the massive stars with a much shorter initial period, of the order of 2 ms. This supernova exploded in a much denser surrounding, estimated at  $\sim 30 \text{ cm}^{-3}$  by Butt et al. (2003), than that one considered for the progenitor of the PSR 1706-44. Note that the average density of the Cyg OB2 association is significantly higher than the above mentioned value. This can be explained by the sweeping effect of the expanding strong



**Figure 3.** The broad band spectrum of the Cyg OB2 association: the diffuse X-ray emission (Chandra - Butt et al. 2003), the GeV  $\gamma$ -ray emission from the EGRET source 3EG J2033+4118 (Hartman et al. 1999, Lamb & Macomb 1997), the TeV emission from the HEGRA source (Aharonian et al. 2002). The cosmic ray flux at EeV energies is marked by the filled circles (CR). The spectra of Vela type pulsars i.e., the Vela pulsar (V) and PSR 1706-44 (P), are shown by the thin dotted curves. The synchrotron and IC spectrum from the nebula around the pulsar are shown by the full and dashed curves, respectively. These spectra are reported for two targets of soft photons inside the nebula: (1) only the MBR and synchrotron photons (thin dashed curve); (2) additional infrared photons from the nebula (thick dashed). The spectrum of  $\gamma$ -rays from collisions of hadrons with the matter inside the nebula is shown by the dot-dashed curve. The spectra of neutrons (included their decay during propagation from the distance of 1.7 kpc) and  $\gamma$ -rays, produced in hadronic collisions by nuclei captured in dense regions of the Cyg OB2, are shown by the dot-dot-dot-dashed and thick dotted curves, respectively.

wind created by the massive, pre-supernova star. Because of the shorter initial period of the pulsar and the higher density medium, the nebulae around the PSR 1706-44 and the pulsar in the Cyg OB2 should differ in some aspects.

In terms of the hadronic-leptonic model discussed by Bednarek & Bartosik (2003), we calculate the synchrotron and the IC spectra produced by leptons, which gain energy in the resonant interactions with nuclei, and the  $\gamma$ -ray spectra from decay of pions, produced in the interactions of nuclei with the matter inside the nebula. An example equilibrium spectra of leptons and nuclei inside the nebula  $2 \times 10^4$  yrs after supernova explosion are shown in Fig. 1. In these calculations it is assumed that the surface magnetic field of the pulsar born in the Cyg OB2 association is equal to  $6 \times 10^{12}$  G, and its initial period of 2 ms. Note, that the rotational energy lost by such a pulsar contributes significantly to the total energy budget of the expanding nebula.

The nuclei with the equilibrium spectrum interact with the matter of the PWN producing  $\gamma$ -rays via decay of pions. These  $\gamma$ -ray spectra are calculated by applying the scaling break model for hadronic interactions proposed by Wdowczyk & Wolfendale (1987). The  $\gamma$ -ray spectra emitted  $2 \times 10^4$  yrs after supernova explosion are shown in Fig. 3. Note that the level of this  $\gamma$ -ray emission is consistent with the flux reported by the HEGRA group. The situation with the synchrotron and IC spectra produced by leptons is more complicated since the low energy photon target inside the nebula is not precisely known. First, we consider the case when the soft photon field is created only by the microwave background radiation (MBR) (the energy density of synchrotron photons is already negligible for a  $2 \times 10^4$  years

old nebula). The results of calculations of the synchrotron and IC spectra from the nebula with the age of  $2 \times 10^4$  yrs are shown in Fig. 3, assuming that the efficiency for lepton acceleration by the nuclei is equal to  $\xi = 0.05$ . Such low efficiency is required in order not to exceed the limit on the diffuse X-ray emission from the Cyg OB2 observed by the Chandra telescope (Butt et al. 2003). Next, we increase the soft photon field inside the nebula by adding the infrared photons produced by the gas inside or around the nebula. The temperature of this radiation is 100 K and the average energy density is 5 times higher than that of the MBR. The synchrotron and IC spectra calculated with the presence of this additional infrared target are shown by the thick dashed curve in Fig. 3, using this same efficiency of lepton acceleration as before. It is evident that only the model with the additional infrared target inside the nebula can produce IC  $\gamma$ -ray flux on the level consistent with reports by the HEGRA group. However, this emission has a much steeper spectrum above 1 TeV, spectral index  $\sim 2.5$ , than that one from the decay of pions. Therefore, the observations of TeV J2032+4130 at energies below 1 TeV should decide which processes, hadronic or leptonic, play the main role in this source. The comparable contribution of both processes to the  $\gamma$ -ray flux at  $\sim 1$  TeV requires fine tuning of the acceleration efficiency of leptons by the nuclei to the value mentioned above.

## 5 CYGNUS CR EXCESS - A REMNANT OF VERY YOUNG PULSAR

The pulsar with the initial parameters:  $P_0 = 2$  ms and  $B = 6 \times 10^{12}$  G, can generate electric potentials in which in principle nuclei can be accelerated above  $\sim 10^{18}$  eV per nucleon (see Eqs. 1 and 2). Nuclei with such energies will soon leave the nebula around the pulsar and propagate in the surrounding medium. The model discussed above for the evolution of the PWNa allows us to calculate the radius of the nebula and the magnetic field inside the nebula at an arbitrary time (see Fig. 2b and also Fig. 1 in Bednarek & Bartosik 2003). Nuclei injected inside the nebula at the time,  $t_{\text{acc}}$ , escape from it at the time,  $t_{\text{esc}}$ , if their diffusion distance,  $R_{\text{dif}}$ , in the magnetic field of the nebula is equal to the dimension of the nebula,  $R_{\text{Neb}}$ , at the time  $t_{\text{esc}}$ . When estimating the escape time of nuclei from the nebula we take into account the structure of the magnetic field inside the nebula (its dependence on the radius), described by the model of Kennel & Coroniti (1984). Also the time evolution of the magnetic field at the pulsar wind shock is taken into account. The diffusion of nuclei through the nebula is determined by the diffusion coefficient

$$D_{\text{dif}} = (cR_L/3)^{1/2}, \quad (4)$$

where  $R_L = E_{Fe}/eZB(t)$  is the Larmor radius of nuclei,  $B(t)$  is the magnetic field inside the nebula at the time  $t$ . The distance travelled by the nuclei is then obtained by integration over the time from the moment of injection up to the escape (see for details Bednarek & Protheore 2002),

$$R_{\text{dif}} = \int_{t_{\text{acc}}}^{t_{\text{esc}}} \sqrt{\frac{3D}{2t'}} dt'. \quad (5)$$

The above mentioned condition,  $R_{\text{dif}} = R_{\text{Neb}}$ , allows us to determine the moment when nuclei with different energies and injection time escape from the nebula. The spectra of nuclei which managed to escape from the nebula during the first  $2 \times 10^4$  yrs after explosion of supernova are shown in Fig. 4, assuming the initial parameters of the pulsar and nebula as considered above. Our calculations show that nuclei with the Lorentz factors above  $\sim 10^6$  should diffuse out of the nebula into the surrounding medium during the first  $2 \times 10^4$  yrs.

We consider the situation in which the pulsar (and its nebula) is formed inside or close to the high density regions of the Cyg OB2 association. The nuclei with the highest energies, Lorentz factors  $\sim 10^9$ , which escaped into the galactic medium with the magnetic field of  $\sim 5 \times 10^{-6}$  G, have the Larmor radii of  $\sim 200$  pc, and diffuse during  $2 \times 10^4$  yrs up to  $R_{\text{dif}}^{\text{ISM}} \sim 600$  pc from the Cyg OB2. It is likely that a part of these nuclei can be captured by dense regions for  $\sim 10^4$  years. The magnetic fields in dense molecular clouds are much stronger than in the Galactic medium, and can reach the values of  $\sim 10^{-4} - 10^{-3}$  G (e.g. Crutcher 1999). In such magnetic fields, the Larmor radius and the diffusion distance of nuclei with the Lorentz factors  $\sim 10^9$  are  $\sim 10$  pc and  $\sim 140$  pc during the time of  $2 \times 10^4$  years. These distances are close to the radius of the central core in the Cyg OB2 estimated on  $R_{\text{OB2}} \sim 15$  pc and to its diameter of the equal to  $\sim 60$  pc. Therefore, since the pulsar is close to the Cyg OB2, we estimate that up to  $\xi \sim (R_{\text{OB2}}/R_{\text{dif}}^{\text{ISM}})^{-3} \approx 10^{-5}$  of all injected nuclei can be captured by the nearby Cyg OB2.

The spectra of nuclei which escaped from the PWNa are shown in Fig. 4. Nuclei with different mass numbers were produced in fragmentation of heavy nuclei (the iron group), occurring during their collisions with the matter of the expanding supernova remnant during the first several years after explosion, when the column density of matter was still large. Note that two groups of heavy nuclei can be distinguished in the total spectrum (see Fig. 4). The higher energy heavy nuclei escape from the supernova envelope just after their injection into the nebula by the pulsar since their Lorentz factors are large enough that corresponding Larmor radii are comparable to the dimension of the nebula at that time. On the other hand, the lower energy heavy nuclei escape from the nebula at a later time ( $\sim 10^3$  years), after suffering significant adiabatic energy losses due to the expansion of the nebula.

We calculate the flux of neutrons produced in collisions of nuclei with the matter inside the Cyg OB2 association. The average density of matter in the Cyg OB2 is estimated at  $\sim 300 \text{ cm}^{-3}$ , for the core radius of the Cyg OB2 equal to 15 pc and its total mass of  $\sim 10^5 M_{\odot}$ . It is assumed that in a single collision, the nuclei are split into two lower mass stable nuclei with the rest of nucleons released free. The energies of these nucleons are reduced by a factor of two in comparison to energies of nucleons in primary nuclei. The flux of neutrons produced in this process is shown in Fig. 3. Interestingly, the neutron flux calculated in terms of the model discussed here, is consistent with the excess of cosmic ray events at energies  $\sim 10^{18}$  eV, reported from the Cygnus region by the AGASA group equal to  $\sim 8\%$  of the cosmic ray flux (Hayashida et al. 1999b).

## 6 CONCLUSION

We have shown that different types of high energy phenomena observed from the direction of the Cyg OB2 association can be self-consistently explained by the model of energetic pulsar created in the recent explosion of one of the massive stars. The pulsar should have the initial period close to 2 ms. For the present age of  $2 \times 10^4$  yrs, its period should be close to  $\sim 210$  ms, if its surface magnetic field is  $6 \times 10^{12}$  G. Such a pulsar belongs to the family of the so-called Vela type pulsars, producing pulsed  $\gamma$ -rays with the intensity comparable to the EGRET source, 3EG J2033+4118, observed in the direction of the Cyg OB2. In fact, the spectral features of 3EG J2033+4118 (possible break in the spectrum, required high energy cut-off) are characteristic for the spectra of the Vela pulsar and the PSR 1706-44. Therefore, we encourage the searches of the hundred millisecond periodicity in the  $\gamma$ -ray sources reported in the direction of the Cyg OB2.

The pulsar in the Cyg OB2 should also be surrounded by the pulsar wind nebula, as observed in the case of other Vela type pulsars. We propose that the TeV  $\gamma$ -ray source reported by the HEGRA group is due to the  $\gamma$ -rays produced by leptons and/or hadrons accelerated by the PWNa inside or close to the Cyg OB2. Therefore, in spite of the close physical relation, the TeV  $\gamma$ -ray emission from the Cyg OB2 (produced in the PWNa) do not need to connect smoothly with the GeV  $\gamma$ -ray emission (produced in the pulsar magnetosphere).

We also suggest that the cosmic ray excess, observed

from the Cygnus region by the AGASA experiment, is also physically related to this energetic pulsar. The highest energy nuclei, injected by the pulsar soon after its formation, escape from the PWNa. A part of these nuclei can be captured by the strong magnetic fields in the high density regions of the Cyg OB2. These nuclei collide with the matter of the Cyg OB2, injecting neutrons which create the observed excess of cosmic rays in the direction of the Cyg OB2.

The  $\gamma$ -rays from the Cyg OB2, produced in collisions of hadrons with the matter, should also be accompanied by the comparable fluxes of neutrinos. However, the predicted muon neutrino event rate in a 1 km<sup>2</sup> detector of the Ice-Cube type during a 1 yr observation is rather low (based on the calculations of the likelihood of detecting neutrinos by such a detector obtained by Gaisser & Grillo (1987), and the absorption coefficients of neutrinos in the Earth derived by Gandhi (2000)). We estimate that hadrons captured in the dense regions of the Cyg OB2 should give between  $\sim 0.14$  to  $\sim 0.05$  neutrino events per year, for the source observed close to the horizon (not absorbed by the Earth) and from the Nadir direction (absorbed by the Earth), respectively. The hadrons confined in the PWNa should produce  $\sim 0.48$  ( $\sim 0.46$ ) events per yr for the source located at the horizon (the Nadir). The spectra of neutrinos produced by hadrons in the PWNa and the Cyg OB2 are shown in Fig. 5. Neutrino spectra produced in the Cyg OB2 are above the atmospheric neutrino background expected within 1° of the source but they are below the sensitivity of the 1 km<sup>2</sup> neutrino detector. On the other hand, the neutrino spectra produced inside the PWNa are closer to the sensitivity limit of the 1 km<sup>2</sup> detector but they are significantly below the atmospheric neutrino background. Therefore, we do not predict any detection of neutrinos from the direction of the Cyg OB2 association.

Finally, we conclude that the presence of at least one Vela type pulsar in the Cyg OB2 association is quite likely on statistical grounds, since the supernova rate in this association should be one per a few tens of hundreds years on average (the Cyg OB2 contains about 100 O type stars with the lifetime of a few million years).

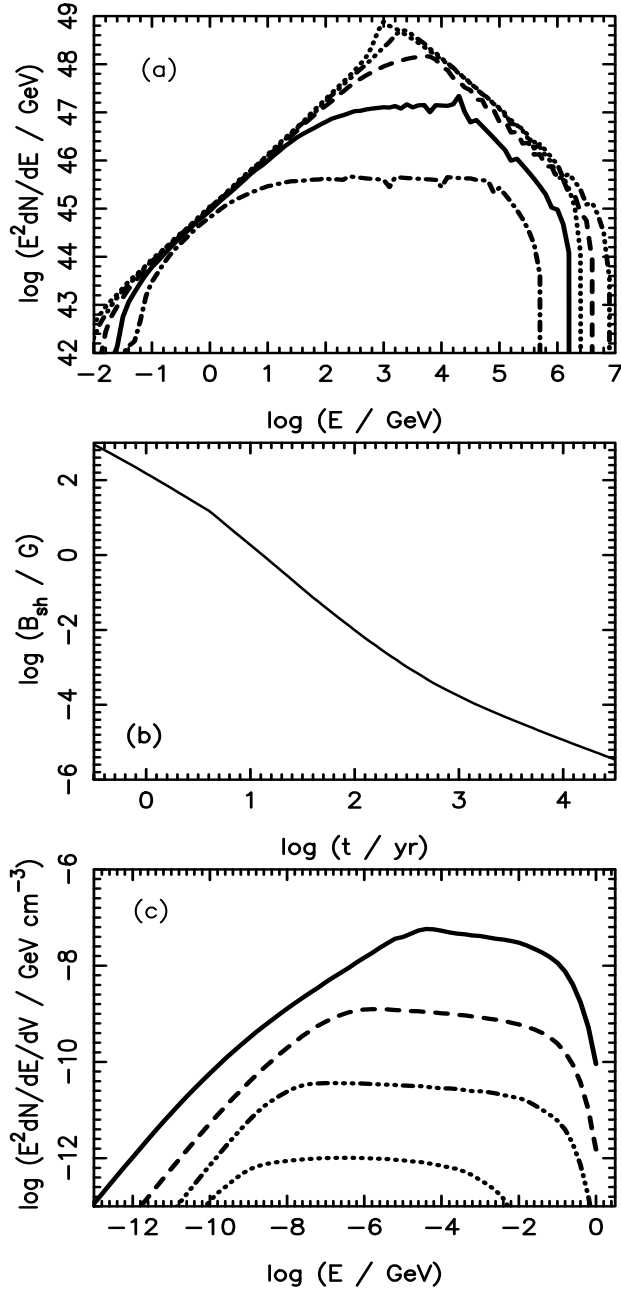
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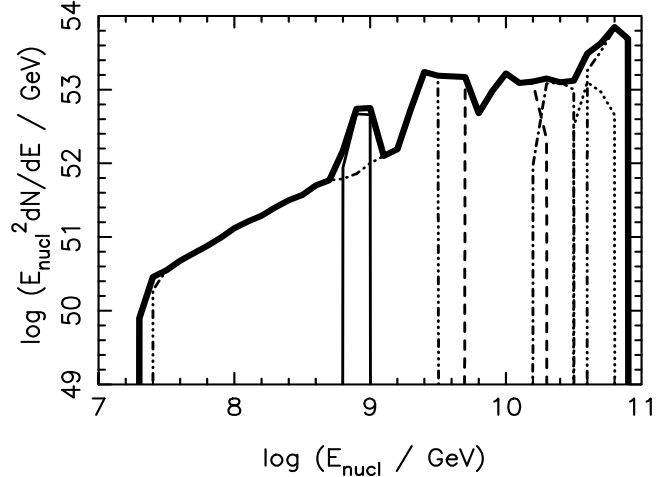
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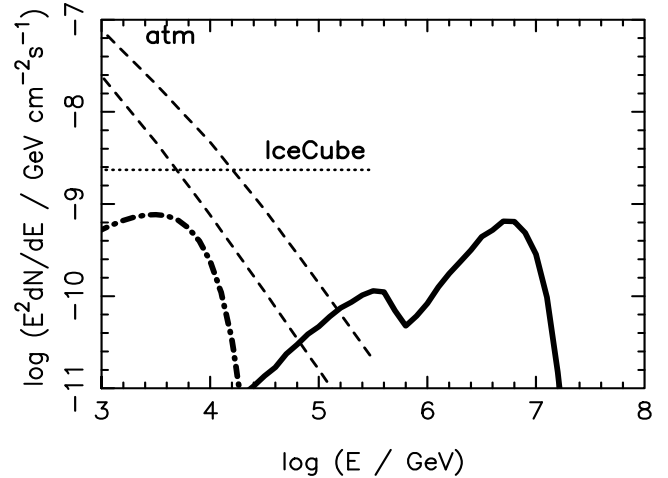
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**Figure 2.** (a) The equilibrium spectra of leptons inside the nebula, injected with the power law spectrum as discussed in the main text, calculated for the pulsar with an initial period of 2 ms and a surface magnetic field of  $6 \times 10^{12}$  G, and the supernova with a mass of  $4M_{\odot}$ , expanding with an initial velocity of  $2000 \text{ km s}^{-1}$ , are shown for different time after a supernova explosion (and a pulsar formation)  $10^2$  yrs (dot-dashed curve),  $3 \times 10^2$  yrs (full),  $10^3$  yrs (dashed),  $3 \times 10^3$  yrs (dot-dot-dot-dashed), and  $10^4$  yrs (dotted). (b) The magnetic field strength in the pulsar wind postshock region (inside the nebula) as a function of time. (c) The differential density of synchrotron photons inside the nebula at a specific time (the curves are marked as in figure (a)).



**Figure 4.** The spectrum of nuclei (thick curve) which escaped from the pulsar wind nebula into the surrounding medium. The spectra of nuclei with different mass numbers are shown by: the thin full curve (protons), dashed curve ( $A=2-10$ ), dot-dashed curve ( $A=11-20$ ), dotted curve ( $A=21-40$ ), and dot-dot-dot-dashed curve ( $A=41-55$ ). It is assumed that the pulsar was born  $2 \times 10^4$  yrs ago with the initial period of 2 ms and the surface magnetic field of  $6 \times 10^{12}$  G, and the initial velocity of the supernova remnant is  $2000 \text{ km s}^{-1}$  and its mass is  $4 M_{\odot}$ .



**Figure 5.** The spectrum of muon neutrinos, produced by hadrons captured in the high density regions of the Cyg Ob2 association (full curve) and produced by hadrons inside the PWN (dot-dashed curve), are compared with the atmospheric neutrino background (dashed curves) within  $1^\circ$  of the source for the zenith and azimuth directions (Lipari 1993). The 3-yr sensitivity of the IceCube detector is marked by the dotted line (Hill 2001).